VŠB – Technická univerzita Ostrava
Fakulta elektrotechniky a informatiky
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Analýza využitelnosti jednovidových optických vláken různých standardů v interferometrickém měření

Analysis of the usability of singlemode optical fibers of different standards in interferometric measurements

2013 **Hynek Prudel**

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Zadání bakalářské práce

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Studijní program: B2647 Informační a komunikační technologie

Studijní obor: 2601R013 Telekomunikační technika

Téma: Analýza využitelnosti jednovidových optických vláken různých standardů v interferometrickém měření
Analysis of the Usability of Singlemode Optical Fibers of Different Standards in Interferometric Measurements

Zásady pro vypracování:

1. Popište problematiku interferometrických měření.
2. Podrobně popište problematiku Mach-Zehnderova Interferometru.
3. Experimentálně analyzujte různé druhy vláken, jejich opláštění a uložení ve větvích Mach-Zehnderova Interferometru.
4. Porovnejte jednotlivé výsledky a vhodnost konfigurace pro měření frekvenční odezvy.

Seznam doporučené odborné literatury:

[1] LOPEZ-HIGUERA, Jose Miguel. *Handbook of optical fibre sensing technology*. New York: Wiley, 2002, 795 p. ISBN 04-718-2053-9.
[2] DERIKSON, Dennis. *Fiber Optic Test and Measurement*. Upper Saddle River: Prentice Hall, 1998, 795 p. ISBN 01-353-4330-5.
[3] BOTTACCHI, Stefano. *Noise and signal interference in optical fiber transmission systems: an optimum design approach*. Chichester, UK: John Wiley, 2008, 831 p. ISBN 04-700-6061-1.

Formální náležitosti a rozsah bakalářské práce stanoví pokyny pro vypracování zveřejněné na webových stránkách fakulty.

Vedoucí bakalářské práce: **Ing. Jakub Čubík**

Datum zadání: 16.11.2012

Datum odevzdání: 07.05.2013

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Prohlášení studenta

Prohlašuji, že jsem tuto diplomovou práci vypracoval samostatně. Uvedl jsem všechny literární prameny a publikace, ze kterých jsem čerpal.

Dne: *07.05.2013*

Vyzula Paudel
....
podpis studenta

Poděkování

Rád bych poděkoval Ing. Jakubu Čubíku za odbornou pomoc a konzultaci při vytváření této diplomové práce.

Acknowledgment

I would like to thank Ing. Jakub Čubík for his professional help and consultation with creating this thesis.

Abstrakt

Tato bakalářská práce pojednává o měření interferencí jednovidových optických vláken v různých prostředích. Je zaměřena na situace, které mohou nastat v každodenní praxi. Teoretická část popisuje problematiku senzoriky, princip a typy měření interferometrie. Měření v praktické části probíhalo pomocí zapojení Mach-Zehnderova interferometru, kdy měřicí větev byla ovlivňována zvukovými vlnami. Bylo měřeno celkem dvanáct různých situací. Praktická část rovněž obsahuje celkové zhodnocení naměřených výsledků.

Klíčová slova

Analýza, jednovidová optická vlákna, interferometrické měření Mach-Zehnderův interferometr, vibrace

Abstract

This bachelor thesis discusses the measurement interferences single mode optical fibers in different environments. Is focused on situations that can happen in everyday practice. Theoretical part describes problematic of sensors, principles and types of measuring interferometry. Measuring in practical part was done using Mach-Zehnder interferometer. In which measuring arm was influenced using sound waves. Overall there were measured twelve different situations. Practical part also contains an overall assessment of the measurement results.

Key words

Analysis, singlemode optical fibers, interferometric measurements, Mach-Zehnder interferometr, vibrations

List of symbols

Symbol	Unit	Significance of the symbol
α	dB	Attenuation
α	dBV	Attenuation
Δl/l	Pa	Stress
λ	m	Wavelength
ϕ	rad	Phase
π	Mathematical constant	Pi
σ	dimensionless unit	Standard deviation
E	V m^{-1}	Electric field
f	Hz	Frequency
I	A	Electric current
l	m	Meters
P	W	Power
P	Pa	Pressure
T (t)	°C	Temperature Celsius
U	V	Voltage
V	l	Volume
V	%	Visibility

List of Abbreviations

Abbreviation	Meaning of the abbreviation
2D	Two dimensional
3D	Three dimensional
DC	Directional Coupler
DFB	Distributed Feedback Laser
FC/APC	Fiber-optic Connector/Angled Physical Contact
FOS	Fiber Optic Sensors
ITU-T	International Telecommunication Union Telecommunication Standardization Sector
LDM	Laser Diode Module
OFS	Optical Fiber Sensors
OS	Optical Sensor
PS	Photonic Sensor
TTL	Transistor–transistor logic

Contents

1 Introduction

Singlemode optical fibers are nowadays more and more used in the sensing and communication field. With increasing demands on higher speed, reliability and further reach are optical fibers used more often.

This bachelor thesis examines influence of sound waves to different optical fibers in different situations. Examined situations come from practice.

All measuring are based on Mach-Zehnder interferometer. Whole principle of Mach-Zehnder interferometer is described in more detail in chapter 3.2. And whole measuring procedure is described in detail in chapter 4. As it was said before measuring was based on Mach-Zehnder interferometer. Measuring and reference arms were placed on wooden boards isolated from stable construction with rubber pads. Also every measuring case is described in chapter 4.

The goal is find out how will singlemode optical fibers respond to excitation by sound waves from loudspeaker in different situations. Because measurements like these were never done before. Situations starting with optical cable placed on wooden board and ending with optical cable placed in soil.

All conclusions are described in more detail in appropriate chapter 5.

2 Sensors

For this bachelor thesis is necessary to clarify few basic concepts. Let's start with sensors. We use sensors in everyday life without realizing it. Human senses and ability to see, hear, touch taste, feel etc. are able because human body has a lot of sensors. These sensors transform environmental influences to electrical impulses that our brain can process. And therefore we have these senses that were mentioned before. Take an example. A sound is detected by the ear, which translates the sound pressure from surroundings into the corresponding electrical ones, which are guided through biotic conductors to the brain. The brain receives, processes and interprets them and then takes decisions and proceeds to give the corresponding orders. This same think is with all other human sensing organs like eyes, nose, skin etc.

Unfortunately these human sensors are not good enough for measuring and any other technical use. Basically it is due to their limitations and that every human is different. Other thing is that these days in Information Era, information is generated, processed, stored, presented and transmitted in ever increasing amounts. Humans are not capable to process and understand so many information and data. These days we work with frequencies, wavelengths and many other variables that human perceptual organs cannot even notice them. Take an example. Human eye can detect light with a wavelength from 380 nm to 780 nm. But nowadays there are used lasers with wavelength typically 1550 nm. Other aspect is that light source as laser is harmful and dangerous.

Nowadays, when computers and electronic devices interfere with our everyday life, we need to capture and process information more than before. We need to detect a process many types of variables it order to obtain more information, automation or a better decision-making capacity in system and subsystems. This effect different sectors of our live like biomedicine, aeronautics, civil engineering, transport, automotive, informatics, robotics, environment, health, home, etc. That is the reason why we need to develop capacity to efficiently capture, quantify and transform any type of physical or chemical magnitude to another domain. For best understanding by computing it is electrical domain.

“The analysis of the above-mentioned systems, leads to the conclusion that in all of them the object variable, which is in a particular physical or chemical state (generally not electrical), is translated to a domain or domains in which the corresponding signals can be transmitted, processed or adapted, constituting what is understood to be a sensor system or sensor. The necessity for more efficient telecommunications has brought about great research efforts in the quest for communications systems, which are lighter, faster, more capable, more reliable and cheaper. This has given rise to great advances both in devices and, of course, in fiber optics. As usually happens, technology developed with one aim sooner or later affects other adjacent areas and so the possibility of making special fibers and devices is contributing decisively to the development of a type of sensor, which uses photonic concepts and materials. Thanks to the features of these sensors, they can frequently be used to substitute conventional ones and when the latter cannot be used, they provide an alternative. These developments have given rise to the birth of the new and growing area of Photonics, Photonic Sensors (currently referred to as Optical 'Sensors) and closely related technologies.” [1]

2.1 Fiber Optic Sensing Technology

Logically, the first task is to explain the term, which gives the name to the corresponding area of photonics, to this book and to this section. Let us answer the question, 'What is a Photonic/Optical Sensor?'.

In accordance with the concept suggested in the introduction of this chapter, we can say in a wide-ranging way which, a sensor system or sensor is usually made up of a converter device, a communication channel and a subsystem for generating and/or detecting, treating, processing, and conditioning the signal. All of these features can be either integrated or not integrated. If there is luminous radiation used in any of the subsystems, the photonic system is understood as a Photonic Sensor (PS) or, as is also commonly used, Optical Sensor (OS), in which the converter is the subsystem which usually, determines and characterizes of the sensor.

According to previous facts we can say, which in general a Photonic/Optical Sensor is a photonic system in which the measured object magnitude, measurand, or input signal (V_i), introduces modifications or modulations in some of the characteristics of light in an optical system. After detecting, processing and conditioning, the system will deliver an output signal (V_o), usually in the electric domain, which is a valid reproduction of the object variable. Transferred or reflected light can be modulated by the measurand or modulating signal in its phase, frequency, amplitude or polarization characteristics. According to this concept, if any of these processes or its parts use a fiber-optic technology, a subdivision of OS known as Fiber Optic Sensors (FOS) of Optical Fiber Sensors (OFS) is created. Considering all above listed, Fiber Optic Sensing Technology can be understand as everything which can be used (the platform of knowledge, techniques, processes, etc.) in order to obtain Fiber Optic Sensors.

In accordance with the above, we can say which field of PS/OS includes also sensors which can create image and which implement near, remote or contactless sensing. Image-formatting Optical Sensors use all types of optoelectronic and optical technologies to capture, treat and process images, and roll all information about object.

2.2 Optical Sensor Types

This part is especially given to non-image-forming sensors, which can be referred in many different ways. To achieve this goal, there are used reference points. They have minimal difference level between each other and complement and let us create logical, conceptual basis for right defining and naming optical fiber sensors.

If we want to solve a sensing problem using well-organized procedure, we should ask several questions such as:

A) What magnitude is to be measured?

B) How should the variable be determined spatially?

C) What should the optical transducer device be like?

D) What modulation technique would optimize the sensor system?

E) Which technology would be suitable?

Answers to this question can produce 'blocks, nodules or types' which need to be denominate, determine, identify, differentiate and typify, sensor systems and devices in precise and representative way.

3 Interferometry

Optical interferometry was for long time connected with precision of metrology, and is essential by the fundamental length standard is transferred to practical measurement. Optical interferometer is an instrument, which can be used to compare two or more optical path lengths. When two or more mutually coherent beams of light use two or more different paths fall on a square-law detector, then we can notice the difference in intensity that is caused due to path difference with a period equal to the optical wavelength. This, differences of optical path lengths can be measured on the scale of the wavelength of light.

With the advert of single-mode optical fibers and related components it was possible to devise interferometers, which are sufficiently robust for using in applications outside metrology laboratories. Nowadays optical fiber interferometers are the basis of wide range of new types of measuring devices. The transduction principle is the modulation of the optical path length of a fiber-sensing element in response to the measurand. Changes in the optical path are measured by interferometry and the measurend is accordingly revealed.

“It is now more than 25 years since the connection between the optical path length of a fiber-guided mode and the physical environment was first recognized, during research into coherent optical communication systems. There quickly followed the realization that the environmental-dependence of path length in single-mode optical fibers could be used to measure temperature and strain. The earliest major research programme on optical fiber sensors was for applications in acoustic pressure sensing, in hydrophones.” [1]

In single-mode systems, there is range of physical measurands, which can be transduced to phase or polarization modulations, significant in terms of three phase constants. An interferometer converts phase changes to intensity changes. The simplest type of interferometry for visualization is an optical arrangement, which causes two mutually coherent light beams that follow two physically different paths. One of these paths contains sensing fiber and the other path is used as reference fiber. When these two light beams are combined on a non-linear detector then they produce a resultant intensity, which is changed periodically with the phase difference, with periodicity 2π. This arrangement is suitable for sensors based on modulation ϕ_1, in the terminology of the analysis mentioned above. Polarization detector can be imagine as one in which the two light beams occupy essentially the same volume of space but are distinguished by the orthogonality of their states of polarization.

“In order to make the two orthogonal states interfere on a non-linear detector, they must each other be resolved to give components in a common direction. For example, by placing a polarizer in the output of a highly birefringent fiber, the two modes are made to interfere provided that the azimuth of the polarizer does not coincide with that of just one of the modes. All practical detectors of optical radiation are non-linear in that they respond to the *power* of the radiation rather than its electric field strength, averaged over some time period which is long in comparison with the period of an individual optical wavelength.” [1]

3.1 General Principles

Optical sensor can be formally defined as a device, which modulates optical signal in response to a measurand field. Assume, that light source has some precisely defined wavelength spectrum and electronic field at wavelength λ is $E(\lambda)$ in unit bandwidth. If the corresponding received electric field is $E'(\lambda)$ then

$$E'(\lambda)=T(X,\lambda)E(\lambda) \tag{3.1}$$

where $T(X,\lambda)$ is propagation matrix describing capturing element and X is vector describingphysical environment, including terms that represents temperature, stress and electromagnetic fields. Function of processing the signal used in the sensing system is to invert to find T, invert it again and find X, and then find out and evaluate according components of X recover requested measurand. As we can see an interferometric sensor effect of the measurand is to modulate the phase of electronic field, where phase is converted to an intensity change in the interferometer.

It is illuminating to express T as a product of conditions, that each describing a physically observable effect on the transmitted beam, like this

$$T = ae^{j\phi l} B \tag{3.2}$$

where a is the scalar transmittance, ϕ_l the mean phase retardation and B the birefringence matrix of the element; a, ϕ_l, and B are all both dispersive and environmentally sensitive.

In single-mode fibers is capturing of measurand possible by modulation one or more of these parameters a, ϕ_l, and B. However in practice transmittance can indicate only weak environmental sensitivity and that is the reason why sensors are generally based on phase and polarization modulation, recovered using interferometry and polarimetry respectively. It is necessary to mention the only the ellipticity and azimuth of the state of polarization of the guided beam. So that the polarization properties of the guiding medium can be adequately described by the Jones matrix, which is 2 x 2 unitary complex matrix. Therefore we can describe transfer function of a single-mode sensing element as

$$E' = a_0 E e^{i\phi l} B \tag{3.3}$$

where a_0 is a scalar constant (the transmittance) and B is the Jones matrix.

For fiber that has perfect cylindrical symmetry, B is an identity matrix I, but generally it is necessary to consider the effect of birefringence within the fiber. For example, for a linearly birefringent fiber

$$B = B_I \begin{bmatrix} e^{i\phi_2/2} & 0 \\ 0 & e^{-i\phi_2/2} \end{bmatrix} \tag{3.4}$$

Fiber like this is characterized by two linear polarizations, such that ϕ_2 is induced relative phase retardation between the eigenmodes caused by propagation through the fiber. For a circularly birefringent fiber

$$B = B_C = \begin{bmatrix} cos\, \phi_3 & -sin\, \phi_3 \\ sin\, \phi_3 & cos\, \phi_3 \end{bmatrix} \tag{3.5}$$

where a_0 is a scalar constant (the where 2 ϕ_3 is the induced relative phase retardation between the eigenmodes, which in this case are left and right circularly polarized states.

Because of this, it is possible to characterize fiber using these three phase constants ϕ_1, ϕ_2, and ϕ_3. These constants are dependent on the properties of material, fiber geometry and also on physical environment. These phase sensitivities may be exploited either to form fiber optic sensor elements or as the basis of phase or polarization state modulators. Environmental sensitivity of fiber can be expressed in according of dependence of the ϕ_i (i = 1, 2, 3) on external effects such as temperature (T), pressure (P) and stress ($\Delta l/l$), such that

$$\frac{\partial \phi_i}{\partial X} = \frac{2\pi}{\lambda}\left(n_i \frac{\partial l}{\partial X} + l\,\frac{\partial n_i}{\partial X}\right) \quad ; \quad X = T, P, \Delta l, \dots \; ; \; i = 1,2,3 \tag{3.6}$$

where l is the length of the fiber; n_1 is the effective index of the fiber; n_2 is the difference between the refractive indices for the two orthogonal linear polarization states, and n_3 is the difference for the orthogonal circular states. First term in brackets represents physical extension of fiber and second represents changes and differences in refractive index.

The first single-mode fiber intrinsic sensors were true interferometers, which light beam from source was split into two or more fiber-guided paths. Then the beams were recombined back to mix coherently together. From the intensity recorded at the interferometer output we can find out phase differences between paths, ϕ_1. Tools like these are called interferometric, and for optimal performance the states of polarization of the recombining beams should be equivalent. Most of the interferometry fibers are two beam devices, where one fiber is effected to measurand (measuring fiber) and second one is isolated from it (reference fiber).

Consider an optical fiber strain gauge. For simplicity it is assumed, that the sensing element is length of nominally cylindrical symmetric fiber without birefringence. It is also assumed, that measured is clearly axial strain without transverse components. Using of stress to fiber has three effects: first the fiber is physically extended, second the stress adjusts refractive index of the fiber core and third dimensions of core are adjusted. First effect is dominant and in case that the other effects are negligible then increasing the length of the fiber by one wavelength would produce an optical path difference change of one wavelength in the interferometer. However second effect is about 20% as large as the first in fused silica and is of opposite sign to the first, this is reducing slightly the sensitivity. Third effect is more complicated. Effective refractive index of the guided mode lies between that of the core material and the cladding material, and in practical fibers is close to that of the core. Reducing the diameter of core pushes effective refractive index closer to that cladding material. With increasing of axial stress is effective index decreasing. Third effect is negligible in practical fibers. Considering all previous mentioned typical overall strain sensitivity for a fiber at a wavelength of 633 nm is about 6.5 x 10^6 rad/m.

An analog argument is applied at temperature sensitivity where are again three effects: temperature extension of fiber length, core modification of index by thermo-optical effect and thermal extension of core radius. In fused silica the thermal expansivity is small, and it is the second term, which is dominant. The third term, thermal extension of core radius, is negligible. A typical overall thermal sensitivity at 633 nm is 100 rad/K for a 1 m sensing element length.

One can go on to derive the sensitivity of the fiber to other measurands. For example, the effect of pressure on the fiber is to reduce the physical length and diameter, and to modify the refractive index via the stress-optic effect.

The function of interferometer is to transduce phase changes to intensity changes. However, transport function in the simplest case is periodical with period 2π radians. Therefore a challenge in the design of signal processing systems is to recover the phase free of the ambiguity imposed by the periodicity.

For normal fibers with nominal cylindrical symmetry, the polarization term terms ϕ_2 and ϕ_3 are relatively insensitive to the environment, so fiber like this is not generally useful for sensing purposes based on polarization. However highly birefringent fibers were commercially affordable for many years and are suitable for many sensing setups based on modulation ϕ_2 (ellipticity polarization). Reaction of such a fiber to stress or temperature depends on structure of a fiber and especially how is the birefringent indicated. For fibers mentioned above birefringent is indicated by temperature stress. Fiber is made from preform, where coating contains sectors of different coefficient of temperature expansion than main surrounding covering material. This is the reason why the fiber, when it cools down after haul, sets up across the core considerable anisotropic stress.

Consider using fiber like that for measuring temperature. Fiber can be visualized as guiding two linear polarization eigenmodes of azimuth aligned to the principal stress directions, e.g. the horizontal and vertical states of polarization, with distinct effective refractive indices. With change of temperature will change physical length of fiber. Considering that refractive indexes in both modes are different, there is small change in their relative path length. Much more remarkable effect is due to change in stress distribution generated by temperature change, thus changing differences between effective refractive indices of the two modes. Thus sensitivity of sensor like this strongly depends on structure of fiber. One parameter describing structure is polarization beat length, which is the distance over which a path difference of one wavelength accumulates between the polarization eigenmodes. For temperature stressed fibers that are like that described above have a beat length about 3 mm, a typical thermal sensitivity would be about 5 rad/K for an l m sensing length.

Similar argument applies to polarimetric stress measurement. Here, the stress modifies the relative refractive index of the eigenmodes as well as producing a physical expansion of the fiber. It is the changing relative index that dominates.

“Sensors have been developed which are based on the modulation of ϕ_3; that is, devices in which the measurand controls the circular birefringence of the sensing element, thus producing a rotation in the polarization azimuth of the guided beam. The most important class of circular birefringence sensor is formed by those based on Faraday rotation for the measurement of magnetic fields. However, sensors based on circular birefringence modulation have been demonstrated for other measurands. For example, Langeac has reported a thermoineter in which the sensing element was a length of sing1e-mode fiber, which had been twisted to induce a relatively high degree of circular birefringence.” [1]

3.2 Two beam interferometers

A common form of optical fiber interferometer is the Mach-Zehnder configuration, with a simple example shown in *Figure 3.2.1*. The interferometer was developed in years 1891 – 1892 by Ernst Mach (born 18th February 1838 in Brno), his son Ludwig and also completely independently by his Swiss colleague Ludwig Zehnder (born 4th May 1854 in Illnau). The Source is connected to one single mode fiber down lead and then is amplitude-divided in two arms, which can be imagining as representing signal beam and the other one as a reference beam. The measurand modifies the phase of the signal beam, while the reference beam keeps a constant environment. These two beams are then recombined back together in second directional coupler (DC) into two up leads that ends in photo detectors, which gives electrical output according to the indicated power.

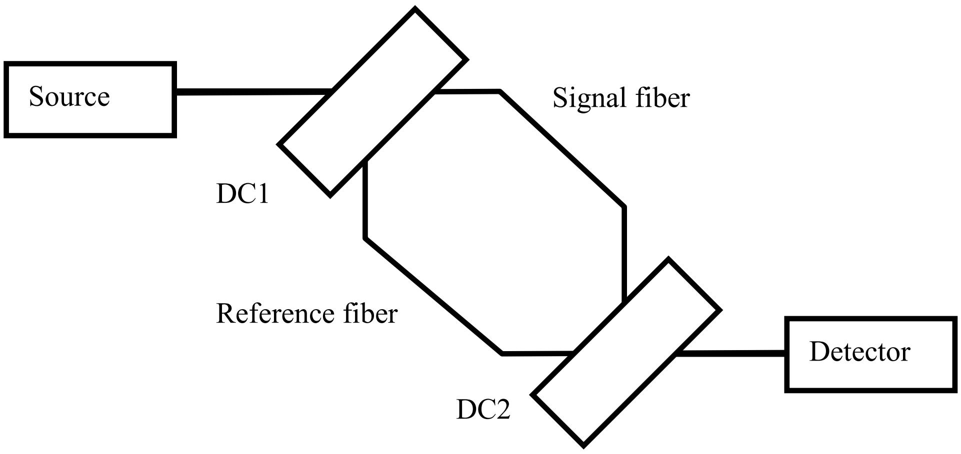


Figure 3.2.1: An optical fiber Mach-Zehnder interferometer.

It can be shown that the detector signals are given by:

$$I_1 = I_0 [l - V \cos(\phi_a - \phi_b)] \tag{3.7}$$

and

$$I_2 = I_0 [1 + V \cos(\phi_a - \phi_b)] \tag{3.8}$$

where ϕ_a and ϕ_b, are phases for signal and reference beams, I_0 is a middle level of signal, and V is the *visibility* of the interference. Visibility depends on relative intensity of signal and reference beams, their relative state of polarization and their mutual coherence. In optimal case, that relative intensities and polarization states are the same and length of optical path difference between signal and reference beam are much smaller, than coherence length of detected light. For good spatial coherence it is necessary to use single-mode fibers. If we keep these optimal conditions visibility is unity. In practical cases visibility can has various value between zero and unity. Notice, that both outputs are in antiphase, so the sum of both outputs is constant regardless relative phase. Having access to both outputs can be used for compensation of effect that is caused by changes in source impulse.

"The relative intensities of the two beams depend on the coupling coefficients of the directional couplers used, fixed during manufacture for those of fused type. The relative state of polarization depends on the birefringence of the fibers and the couplers. Whilst it is possible to fabricate the entire interferometer from highly birefringent fiber and components, and to work with a fixed polarization eigenstate, most interferometers are constructed from normal cylindrically symmetric fiber. Thus environmental effects cause the recombining states to be unequal. Under these circumstances, some form of explicit birefringence control is needed to preserve visibility; one common means is to induce controlled birefringence by bending the fiber. The coherence length is set by the bandwidth of the light at the detector, and is usually dominated by the properties of the source." [1]

Purpose of Mach-Zehnder interferometer is to exact measuring transparent objects, even if it is not as sensitive as Michelson interferometer (*Figure 3.2.2*), which uses two reflectors that reflects back incoming beams and put it back together in directional coupler. Measuring area can be placed far enough from optical elements and referral beam; therefore it is possible to use this interferometer for measurement objects that generate heat flux. Accuracy of measurement can be increased by correction of bending beams, which are effective with interferometers with one passing beam through measured object. Inasmuch as both beams are real interferometer can work with continuous laser source in real time (unless pulse source is used). Device can be set to the finite and infinite width of interference fringes in reference area by rotation of second coupler. Disadvantage of Mach-Zehnder interferometer is necessity to use very high quality lenses, mirrors and splitters.

Using a complex arrangement of the interferometer we can also significantly increase the diameter of the visual field and expand the application of interferometry to more transparent objects occurring in fluid mechanics, environmental engineering etc. [2]

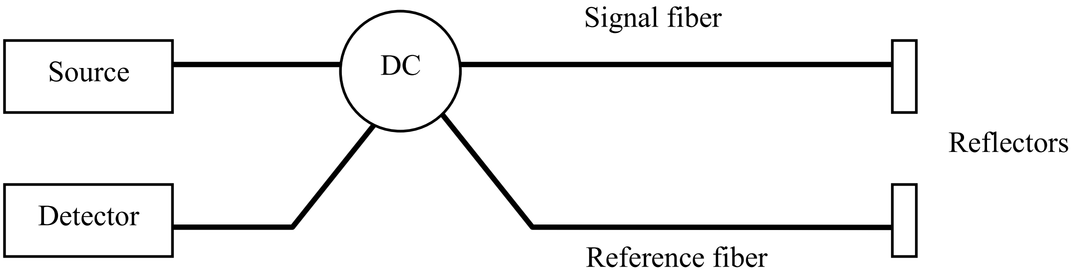


Figure 3.2.2: An optical fiber Michelson interferometer.

4 Measuring

In the following chapters is described what kind of devices and equipment were use and what the each measuring procedure and setup looked like.

4.1 Devices used for measuring

Single-mode fiber: ITU-T G.652D

Bend Insensitive Single-mode fiber: ITU-T G.657 B3 (LG3.0C-001C-DHW)

Couplers: OPTOKON SFT-S35-01x02-50-CM1-SPC-SPC

Detector: Thorlabs – PDA10CS-EC

Source driver: Thorlabs LDC 205 C

Source driver: Thorlabs TED 200 C

Diode: LDM-1550-DC-1-FA 1550nm DFB Laser Diode Coaxial pigtailed, FC/APC

Frequency generator: Hameg HMF2550

Actual parameters:

Wavelength: 1548.59 nm

Power 1.74 mW at 25 °C and current 20 mA.

Temperature of diode set to 25°C.

Current for diode set to 20mA.

Fusion splicer: Sumimoto Type-39

Thermometer: Testo 720

For reference measuring:

Source: Noyes AFL OLS2 Dual

Detector: Noyes OMP4

Soil: PN-78/G-98016 pH w/H_2O/3.0-4.0

4.2 Setup description

Diagram:

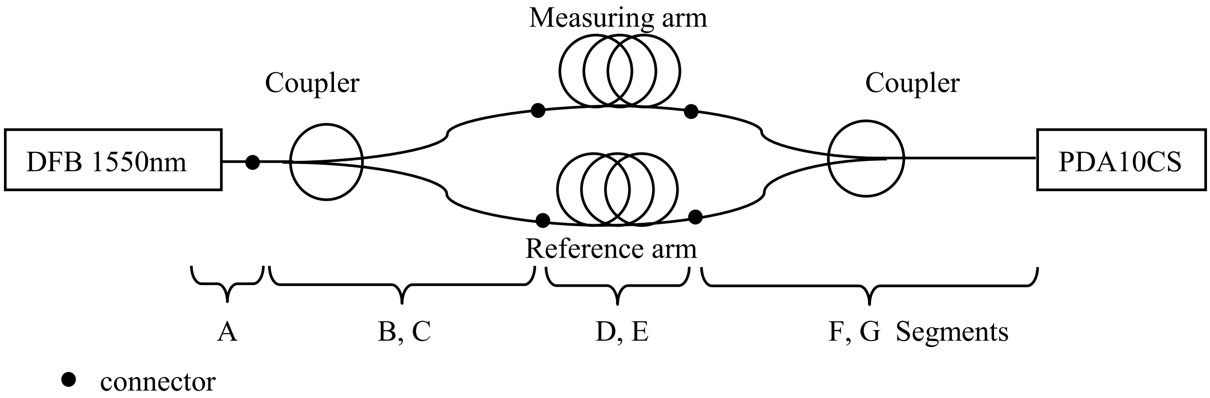


Figure 4.2.1: Diagram of used Mach-Zehnder interferometer.

For excitation there was used TTL signal with frequency of 160 Hz and voltage 10V peak to peak. Height of speaker was 1 m above fiber. Same signal was used for every measurement case.

Because optical fibers are very sensitive to any, even microscopic, dirt it was necessary to clean every connection with isopropyl alcohol and cleaning dust and hair free tissues. Even with precise cleaning it is impossible to make connector connection without any attenuation. Values of attenuation are in Table 4.1. Where segment D is measuring arm and segment E is reference arm.

Table 4.1: Length and attenuation at 1550 nm

Segment	Attenuation [dB]	Length [cm]
A	0.45	100
B	3.68	230
C	3.68	230
D	0.10	210
E	0.32	210
F	3.24	230
G	3.21	230
Overall	6.89	670

Total attenuation is, according to each segment, 7.76 dB at a wavelength 1550 nm. But when the setup was assembled together total attenuation was lower, exactly 6.89 dB. It is probably due to cleaning connections before and after every measuring of segment attenuation that is necessary to ensure lowest possible attenuation.

Measuring segment in mounting foam from cases F and G had attenuation 3.85 dB at a wavelength 1550 nm.

Bend Insensitive Single-mode fiber ITU-T G.657 B3 from cases B and H was necessary to weld pigtails and final attenuation was 0.25 dB at 1550 nm.

Water temperature:

Warm water:

Beginning of measuring: 41.8 °C

Switching of arms: 41.1 °C (from measuring to reference arm)

End of measuring: 40.5 °C

Volume of water: 9 l

Cold water:

Beginning of measuring: 24.5 °C

Switching of arms: 24.6 °C (from reference to measuring arm)

End of measuring: 24.6 °C

Volume of water: 9 l

Soil temperature: 6.0 °C

4.3 Measurement procedures

The whole measurement setup is basically Mach-Zehnder interferometer as you can see on *Figure 4.2.1*. For all measurements were used a loudspeaker located one meter above sensing arm. Signal generator Hameg HMF2550 powered the loudspeaker. As was mentioned before, there was same signal for all measurements. Parameters of TTL signal were frequency 160 Hz and voltage 10V peak to peak. The frequency, voltage and type of the signal were chosen base on several measurement and this setup provides best observable values.

Harmonic Frequency is the audio component that affects the color of sound. Harmonic frequencies are frequencies, which can be expressed in hertz as an integer multiple of the fundamental frequency. For example for frequency 440 Hz harmonic frequencies are 880 Hz (twice), 1320 Hz (three times), 2200 Hz (five times), etc. But 1100 Hz (two and a half times) is not harmonic frequency of 440 Hz. So, all frequencies that are not integer multiples of the fundamental frequency are called enharmonic. In this example enharmonic frequencies for 440 Hz can be 341 Hz, 528 Hz, 2000 Hz, etc.

Harmonic frequencies can also be divided into odd and even. Depending on whether the audio contains more odd-or even-numbered harmonics, other sounds as well. The more harmonic frequencies sound has, the sharper it sounds. Sinusoidal signal contains no higher harmonics (it is also possible to achieve this signal only by modeling, not naturally) rectangle signal contains all. [3]

For the best results and elimination of measurement error there were ten measurements of each case and each arm. Because the detector is very sensitive it was necessary to make longer measurements than a couple seconds. Each measurement was done for about nine to fifteen seconds. As you can see on Figure 4.3.1.

Values were detected and gather using Texas Instruments virtual tool. All 3D and 2D graphs were created from measured data using Matlab software. More about processing data you can find in chapter 4.4 Measurement results.

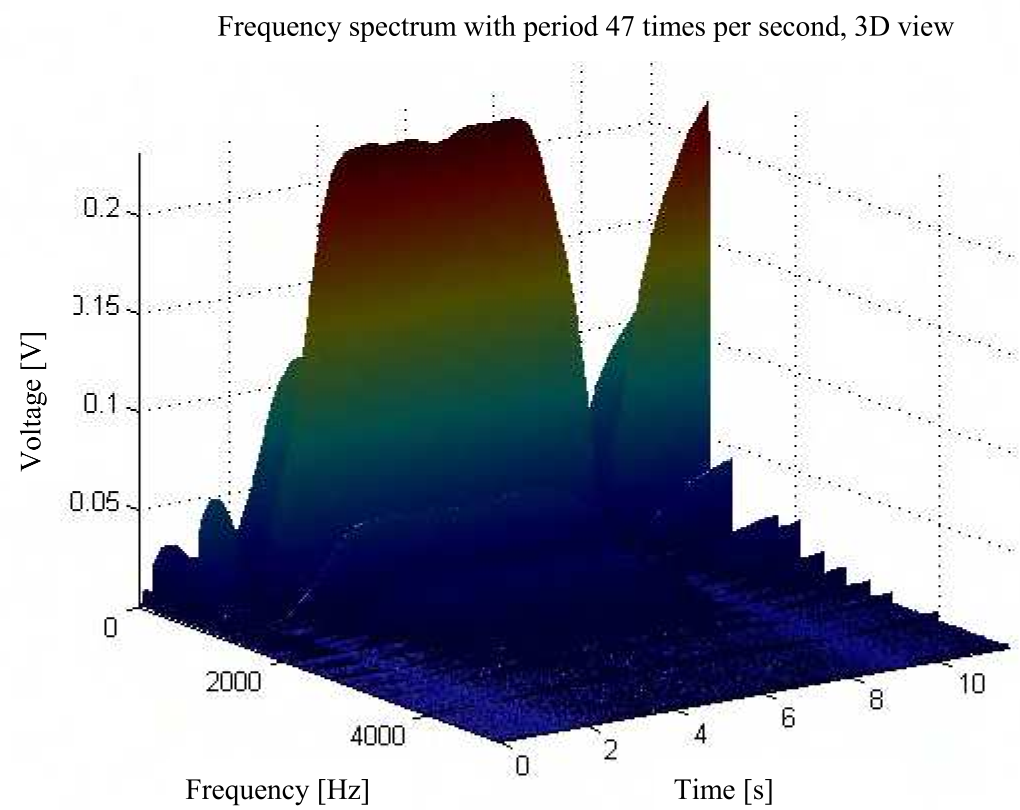
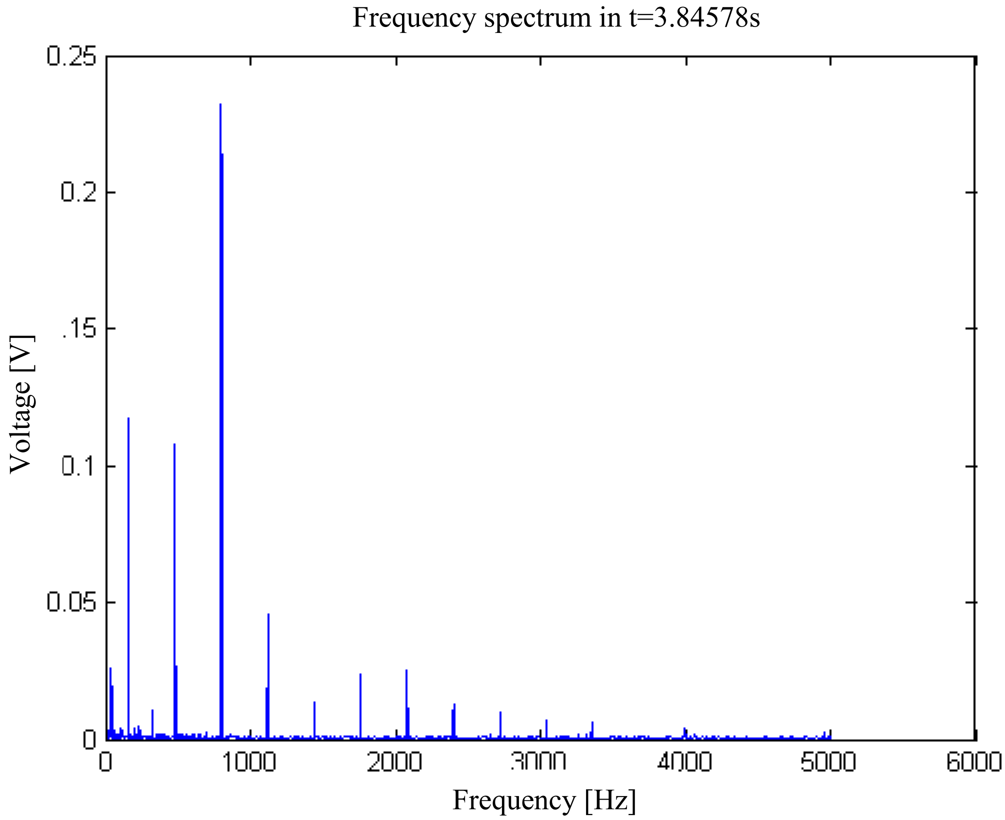


Figure 4.3.1: 3D graph Case B L 10th measuring

This is 3D graph of detected frequencies in time. X-axis represents time in seconds, Y-axis represents voltage in Volts and finally Z-axis represents frequency in Hertz. As you can see on this example graph it is difficult to say what level of voltage should be read. For best-seen differences in every measuring setup it was necessary to select the time where is the level of voltage most uniform. In this case it is in 3.845th second. On Figure 4.3.2 there is 2D representation of level of each frequency for that time. X-axis represents frequency in Hertz and Y-axis represents voltage in Volts.



s

Figure 4.3.2: Frequency spectrum in specific time.

There were chosen several simulations of situations that can occur in real environment. Beginning with the most common optical fiber lying on wooden board, followed fiber covered with polystyrene board, placed between two polystyrene boards, fiber without secondary protection, in mounting foam without secondary protection, fiber placed in water and soil and fiber glued to the wooden board.

Measuring and reference arms were placed on separate wooden boards. Wooden boards were placed on rubber pads to eliminate vibrations from floor. With this setup there were two measurements, each with different type of fiber. First with ITU-T G.652D further in text as Case A and second with ITU-T G.657 B3 further in text as Case B. Inasmuch as the fiber ITU-T G.657 B3 was on reeling with very long length it was necessary to weld pigtails. For this purpose it was used Sumimoto Type-39. Final parameters of this cable were attenuation 0.09 dB at 1550 nm for each end and total attenuation of this 210 cm long cable was 0.25 dB at 1550 nm. Photos of Case B are on DVD in file Photos.

There were two measurements with polystyrene boards. First method was consisted on basic covering the fiber with one polystyrene board, as you can see on Figure 4.3.3 further in text as Case C.

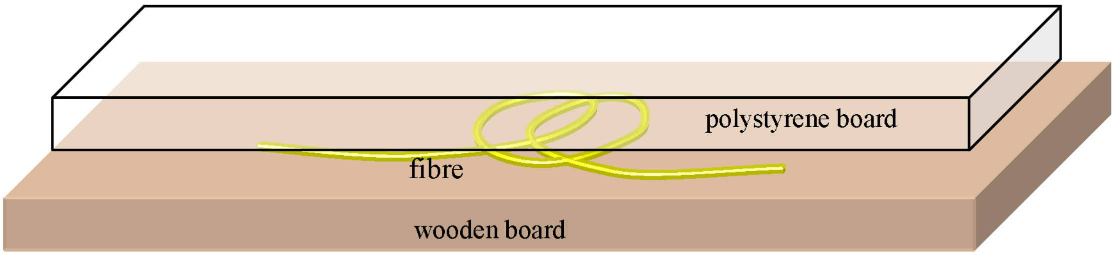


Figure 4.3.3: Scheme of fiber covered with polystyrene board.

Second method was little bit complicated, because fiber was placed between to polystyrene boards. It was necessary to cut a place for the fiber in the bottom polystyrene board. These two boards were fixed together by double-sided adhesive tape. To achieve adequate fixation board were burdened for few minutes. This setup is further in text marked as Case D. This setup is on picture in Annex Photos of Case D are on DVD in file Photos.

Preparing for measuring without secondary protection, further in text as Case E, was not also easy. It was necessary to remove the protection from cable and does not cut the fiber. Process like this has to be done piece by piece. Kevlar threads were also removed. This setup is on a photo on DVD in file Photos.

Measuring with mounting foam was a little bit time consuming. According to the manufacturer´s instructions the foam has to harden for at least 24 hours. Another obstacle was, that it is very difficult or even impossible to extract fiber from fully harden mounting foam. There were three measuring setups with mounting foam. First measuring was with ITU-T G.652D fiber without secondary protection and without foamed supply cables to couplers, further in text as Case F. Photos of Case F are on DVD in file Photos. Second measuring was with fiber without secondary protection and with foamed supply cables to couplers, further in text as Case G. Most difficult was to extract couplers arms from mounting foam with no damage, because these couplers were necessary for further measuring setups. Finally third measuring setup was with fiber ITU-T G.657 B3 foamed just from connector to connector without couplers arms further in text as Case H. Photos of Case H are on DVD in file Photos.

For measuring in warm and cold water was used fiber ITU-T G.652D with secondary protection. It was necessary to place the fiber in the middle of the water, neither on the bottom of the plastic bucker nor keep it floating on the surface. To make sure that the fiber was not on the bottom there was placed a folded rubber belt. But it turns out, that water lifts rubber belt and also fiber. So rubber belt was loaded with an iron square presented on Figure 4.3.4. Photos of Case I are on DVD in file Photos. This setup was measured with two temperatures of water. First with warm water further in text marked as Case I, temperature was from 41.8 °C at the beginning of measuring to 40.5 °C at the end of measuring. Total volume of water was 9 liters. Then the measurement was repeated with cold water further in text marked as Case J with temperature from 24.5 °C at the beginning of measuring to 24.6 °C at the end of measuring. With an equal volume of water as in previous case namely 9 liters.

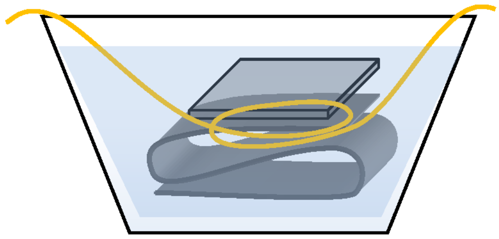


Figure 4.3.4: Scheme of fiber in water.

To make sure that fiber is in the middle was much easier with using soil. It is logical, optical cable is not heavy and if there is and layer of soil it will not go through it. Optical cable was completely covered with another layer of soil. This setup is further in text marked as Case K. For completeness temperature of soil was 6.0 °C. Photos of Case K are on DVD in file Photos.

Last measuring setup was consisted of gluing optical cable to the wooden board with superglue further in text as Case L. Photos of Case L are on DVD in file Photos.

In all measuring setups was reference arm placed on wooden board.

Every measuring case has two outputs. One output for reference arm placed on wooden board. Further in text marked with R. Second output for measuring arm located in different situations. Further in text marked with L. For example Case C L represents measuring results from measuring arm covered with polystyrene board. And Case K R represents measuring results from reference arm from measuring with soil.

4.4 Measurement results

There is too many data from all measuring cases. So it was necessary to separate relevant data from irrelevant data. To do that there was set 10% threshold for all cases and both arms. There was selected maximum value for each of 10 measurements in each case and arm. From these 10 values was calculated arithmetic mean. This arithmetic mean was default value for setting that 10% threshold. So in further tables there will be only values greater than that 10% threshold of arithmetic mean. For example values gathered in Case A L are in Table 4.2 with average and threshold value.

For better clarity values were recalculated according to equation (4.1). Where V_1 is the voltage being measured, V_0 is a specified reference voltage for all cases and values it is 1 V, and G_{dB} is the power gain expressed in decibels.

$$G_{dB} = 20\, log\left(\frac{V_1}{V_0}\right) \tag{4.1}$$

After applying equation (4.1) there are much more convenient values in dBV as can be seen in Table 4.3.

Standard deviation is in probability theory and statistic very often used to determined statistic dispersion. This is root square mean of values and their arithmetic mean.

We can say that this value represents how much different are typical examples is set of examined numbers. If standard deviation is small, that mean that elements of studied set are mostly same to each other and vice versa big standard derivation represents big mutual differences. Standard deviation is most widely used measure of variability. For this operation was used STDEV.P function in Excel. [4]

Table 4.2: Maximum values in V

Measurement	Value [V]
1	0.1381982340
2	0.1505476230
3	0.1542548470
4	0.1574312420
5	0.1574312420
6	0.1596901490
7	0.0894368890
8	0.1355205590
9	0.1394724020
10	0.1185536330
Average	0.1383068410
Threshold	0.0138306841

Table 4.3: Maximum values in dBV

Measurement	Value [dBV]
1	-17.190
2	-16.447
3	-16.235
4	-16.058
5	-17.080
6	-15.934
7	-20.970
8	-17.360
9	-17.110
10	-18.522
Average	-17.183
Threshold	-37.183

In following tables are shown modified values. Tables are divided according to measurements. Each case has its own table with affected frequency and values of attenuation in dBV for left and right arm.

For better orientation we can see brief description of each setup in Table 4.4.

Table 4.4: Description of setups

Case	Description
A	Fiber on wooden board (G.652)
B	Bending insensitive fiber (G.657 D)
C	Fiber covered with polystyrene board
D	Fiber closed in two polystyrene boards
E	Fiber without secondary protection
F	Fiber in mounting foam
G	Fiber in mounting foam with coupler arms
H	Insensitive fiber in mounting foam
I	Fiber in warm water
J	Fiber in cold water
K	Fiber in soil
L	Fiber glued to wooden board

Table 4.5: Case A

Frequency [Hz]	L – Measurement [dBV]	R – Measurement [dBV]	L – σ Frequency [Hz]	L – σ Measurement [dBV]	R – σ Frequency [Hz]	R – σ Measurement [dBV]
160	-22.116	-29.592	1.246	3.581	0.000	1.959
480	-21.251	-30.221	1.706	3.926	0.763	1.235
800	-27.869	-21.109	0.763	3.405	1.706	4.674
1120	-26.018	-20.777	1.246	2.987	1.246	1.956
1440	-29.477	-	0.763	1.737	-	-

Table 4.6: Case B

Frequency [Hz]	L – Measurement [dBV]	R – Measurement [dBV]	L – σ Frequency [Hz]	L – σ Measurement [dBV]	R – σ Frequency [Hz]	R – σ Measurement [dBV]
160	-23.808	-17.201	1.706	4.953	1.706	4.966
320	-	-16.238	-	-	1.706	4.208
480	-23.125	-	1.706	3.800	-	-
800	-18.583	-22.431	1.706	4.230	1.706	4.315
1120	-26.311	-23.735	0.000	2.220	1.246	2.262
2080	-31.448	-	0.000	0.820	-	-

Table 4.7: Case C

Frequency [Hz]	L – Measurement [dBV]	R – Measurement [dBV]	L – σ Frequency [Hz]	L – σ Measurement [dBV]	R – σ Frequency [Hz]	R – σ Measurement [dBV]
160	-30.250	-21.011	1.246	5.420	2.158	7.196
320	-	-31.210	-	-	0.000	1.289
480	-27.460	-30.140	0.763	3.131	0.763	1.154
800	-21.645	-19.792	1.706	4.357	1.706	4.283
1120	-23.442	-22.618	1.246	2.800	1.246	2.850

Table 4.8: Case D

Frequency [Hz]	L – Measurement [dBV]	R – Measurement [dBV]	L – σ Frequency [Hz]	L – σ Measurement [dBV]	R – σ Frequency [Hz]	R – σ Measurement [dBV]
160	-13.096	-18.514	1.246	0.851	0.000	1.862
480	-8.078	-11.530	1.706	3.692	1.706	3.730
800	-8.078	-6.399	1.706	4.167	1.706	4.162
1120	-6.994	-	1.246	2.273	-	-
1440	-14.504	-12.181	1.246	2.462	1.706	4.205
1760	-13.670	-	1.706	3.748	-	-
2080	-	-11.707	-	-	1.246	1.825

Table 4.9: Case E

Frequency [Hz]	L – Measurement [dBV]	R – Measurement [dBV]	L – σ Frequency [Hz]	L – σ Measurement [dBV]	R – σ Frequency [Hz]	R – σ Measurement [dBV]
160	-18.576	-15.662	1.246	2.752	1.706	5.085
480	-21.078	-	1.706	3.749	-	-
800	-21.244	-	1.706	4.308	-	-
1440	-34.308	-	0.000	0.457	-	-

Table 4.10: Case F

Frequency [Hz]	L – Measurement [dBV]	R – Measurement [dBV]	L – σ Frequency [Hz]	L – σ Measurement [dBV]	R – σ Frequency [Hz]	R – σ Measurement [dBV]
160	-13.462	-11.787	1.246	1.826	1.246	1.843
480	-13.194	-15.264	1.706	3.779	0.763	0.617
800	-5.082	-2.984	1.706	4.194	1.706	4.199
1120	-16.538	-9.680	1.246	2.239	1.246	1.786
1760	-17.506	-	0.763	0.386	-	-

Table 4.11: Case G

Frequency [Hz]	L – Measurement [dBV]	R – Measurement [dBV]	L – σ Frequency [Hz]	L – σ Measurement [dBV]	R – σ Frequency [Hz]	R – σ Measurement [dBV]
160	-47.269	-59.691	0.000	6.056	0.763	1.827
480	-56.370	-	0.000	3.797	-	-
800	-	-49.116	-	-	1.706	3.932
1120	-	-53.141	-	-	1.246	1.907
1440	-	-61.647	-	-	0.763	1.679

Table 4.12: Case H

Frequency [Hz]	L – Measurement [dBV]	R – Measurement [dBV]	L – σ Frequency [Hz]	L – σ Measurement [dBV]	R – σ Frequency [Hz]	R – σ Measurement [dBV]
10	-74.485	-	0.000	3.978	-	-
43	-73.872	-65.760	1.246	2.005	1.246	2.808
160	-72.571	-65.880	2.158	6.873	1.706	5.166
480	-75.452	-	0.763	1.243	-	-
800	-73.416	-68.940	1.706	4.425	1.706	4.511
1120	-75.940	-66.728	1.246	2.173	1.246	2.614
1440	-74.135	-68.046	1.246	2.913	1.246	2.901
1760	-	-77.176	-	-	0.763	1.796
2080	-79.461	-76.978	0.763	2.098	0.000	1.138
2720	-78.498	-	1.246	3.054	-	-
3040	-80.907	-	0.763	0.908	-	-

Table 4.13: Case I

Frequency [Hz]	L – Measurement [dBV]	R – Measurement [dBV]	L – σ Frequency [Hz]	L – σ Measurement [dBV]	R – σ Frequency [Hz]	R – σ Measurement [dBV]
160	-31.524	-	0.763	2.756	-	-
800	-24.867	-11.706	1.246	3.580	1.706	4.388
1120	-26.770	-	2.158	6.632	-	-
1440	-32.594	-	1.246	2.991	-	-

Table 4.14: Case J

Frequency [Hz]	L – Measurement [dBV]	R – Measurement [dBV]	L – σ Frequency [Hz]	L – σ Measurement [dBV]	R – σ Frequency [Hz]	R – σ Measurement [dBV]
160	-	-27.964	-	-	1.246	1.820
480	-29.801	-32.635	0.763	0.772	0.763	0.677
800	-18.182	-22.175	1.706	4.160	1.706	4.046
1120	-29.597	-	0.000	0.788	-	-
1440	-	-24.567	-	-	1.706	3.972
1760	-	-35.083	-	-	0.763	0.738

Table 4.15: Case K

Frequency [Hz]	L – Measurement [dBV]	R – Measurement [dBV]	L – σ Frequency [Hz]	L – σ Measurement [dBV]	R – σ Frequency [Hz]	R – σ Measurement [dBV]
160	-27.964	-34.079	1.246	1.820	1.246	5.893
480	-32.635	-38.511	0.763	0.677	0.763	2.025
800	-22.175	-32.178	1.706	4.046	1.706	4.571
1120	-	-34.666	-	-	1.246	2.326
1440	-24.567	-28.057	1.706	3.972	1.706	4.261
1760	-35.083	-36.430	0.763	0.738	0.763	0.782

Table 4.16: Case L

Frequency [Hz]	L – Measurement [dBV]	R – Measurement [dBV]	L – σ Frequency [Hz]	L – σ Measurement [dBV]	R – σ Frequency [Hz]	R – σ Measurement [dBV]
10	-56.636	-61.340	0.763	5.194	0.763	3.576
43	-53.939	-57.167	1.246	4.440	1.246	2.870
480	-56.591	-54.998	1.706	3.444	1.706	3.848
800	-62.059	-53.841	1.706	2.339	1.706	4.398
1120	-	-62.108	-	-	1.246	2.122
1440	-	-63.479	-	-	0.763	1.332

4.5 Discussion about results

Overall I did twelve different measurements. All measured measurements are in tables from Table 4.5 to Table 4.16. For better clarity of final measurements there are all tables with measurements in one table in Annex.A: All measurements results in one table. As you can see in above tables, harmonic frequencies appeared. More about harmonic frequencies is in chapter 4.3 Measurement procedures. In two cases were measured low frequencies below 160 Hz, which are probably caused by resonance. Another fact is that fibers were mainly sensitive to odd harmonic frequencies.

In the basic setup Case A (Table 4.5) that we can consider as a reference measurements. There is connection between excitation frequency and frequencies that was measured. You can see measurements in appropriate Table 4.5. For excitation of all measuring was used 160 Hz and frequencies that occurred are multiples of this measurement – harmonic frequencies. Specifically 160, 480, 800, 1120 and 1440 Hz for measuring arm (left side) and 160, 480, 800 and 1120 Hz for reference arm (right side). Interesting is that higher measurements are in low frequencies 160 and 480 Hz on left side, specifically -22.116 and -21.251 dBV. But on the right side higher measurements are at higher frequencies 800 and 1120 Hz, specifically -21.109 and -20.777 dBV.

Next setup is Case B (Table 4.6). Setup is almost the same as in Case A with the only difference, which is different type of optical fiber. As you can see in appropriate Table 4.6 there is also correlation with excitation frequency. On the left side there are frequencies 160, 480, 800, 1120 and 2080 Hz. With the maximum measurement -18.583 dBV at frequency 800 Hz. As you can see fiber is sensitive at high frequency 2080 Hz. On the right side measured frequencies are 160, 320, 800 and 1120 Hz. This time with maximum measurements -17.201 and -16.238 dBV are at low frequencies 160 and 320 Hz.

Case C (Table 4.7) has almost the same measurements as the previous two cases. Again main frequencies are 160, 480, 800 and 1120 Hz for left side and 160, 320, 480, 800 and 1120 Hz for right side. Highest measurements are -21.645 dBV for left side and -19.792 dBV for left side both at frequency 800 Hz. Lowest measurements are -30.250 dBV at 160 Hz for left side and -31.210 dBV at 320 Hz for right side.

So we can say that there is no significant difference between first three cases.

Gathered measurements in Case D (Table 4.8) shows higher measurements than in first three cases. Left arm is sensitive at frequencies 160, 480, 800, 1120, 1440 and 1760 Hz. Right arm is sensitive at almost same frequencies 160, 480, 800, 1120, 1440 and 2080 Hz. Measurements in left arm are significantly higher than in first three cases. Highest measurement is -6.994 dBV at 1120 Hz, which is more than three times higher than in cases A, B or C at same frequency. The same thing is in right arm. Highest measurement is -6.366 dBV at 800 Hz and again this is more than three times higher than in cases A, B or C at same frequency. Even lowest measurements in this case are also higher than in previous three cases.

From measurements in Case E (Table 4.9) we can see that the fiber is sensitive on left side at frequencies 160, 480, 800 and 1440 Hz. But on right side it is sensitive only at frequency 160 Hz. And the measurement at this frequency is higher, comparing to left side, specifically -15.662 dBV. Lowes sensitivity is in left side -34.308 dBV at 1440 Hz.

In case F (Table 4.10) we can see that there are very high measurements comparing to other cases. Those high measurements are in both sides left and right. Both sides are also sensitive at frequencies 160, 480, 800 and 1120 Hz plus left arm is also sensitive at frequency at 1760 Hz. As I mentioned before there are high measurements especially at frequency 800 Hz specifically -5.082 dBV for left side and -2.984 dBV for right side. These are highest measurements of all cases.

With measuring Case G (Table 4.11) there was a little obstacle. There were very low measurements. For left arm fiber was sensitive only at frequencies at 160 and 480 Hz with measurements -47.269 and -56.370 dBV. Left arm was sensitive at frequencies 160, 800, 1120 and 1440 Hz. The specific levels of measurements for right side are -59.691, -49.116, -53.141 and -61.647 dBV. As you can see there is very big difference between this case and for example Case A. Measured sensitivity in Case G is more than twice lower than in Case A. Also there is a big difference in measurements between this case and Case F. As you can find out sensitivity in Case G is almost three times smaller than in Case F. I suppose it is because of macro bending of measuring fiber and especially coupler arms. This supports fact that measured attenuation of measured arm was 3.85 dB at wavelength 1550 nm, which represents more than 50% signal loss. Growth inhibition is very noticeable comparing to attenuation of plane fiber that was only 0.10 dB at 1550 nm.

Using fiber that is more resistant to macro bends in Case H (Table 4.12) shows sensitivity to many different frequencies. Despite that measurements are very low. Fiber is sensitive at frequencies 10, 43, 160, 480, 800, 1120, 1440, 2080, 2720 and 3040 Hz on left arm. Right arm shows sensitivity at frequencies 43, 160, 800, 1120, 1440, 1760 and 2080 Hz. In both arms appeared frequencies below 160 Hz, which are probably caused by resonance. As I mentioned before measurements are very low in both arms. Specifically, measurements in left arm are between -72.571 and -80.907 dBV that are more than three times smaller measurements than in Case A. And measurements from -65.760 to -77.176 dBV in right arm. Again these measurements are significantly smaller than for example in Case A, approximately two and half times smaller. As you will see further in this chapter, output of this measurement is closest to output from Case L.

With a closer examination of measurements from Case I (Table 4.13) we can see that fiber in left arm is sensitive at frequencies 160, 800, 1120 and 1440 Hz. With detected levels of measurements from -24.867 to -32.594 dBV. That is almost the same as in Case A. But in right arm was fiber sensitive only at one specific frequency 800 Hz with level of -11.706 dBV.

On the other hand Case J (Table 4.14), setup with cold water, shows different measurements. First fiber in left arm was sensitive at frequencies 480, 800 and 1120 Hz. Levels of measurements are little higher than in Case I, specifically from -18.182 to -29.801 dBV. Fiber in right arm was sensitive at frequencies 160, 480, 800, 1440 and 1760 Hz. With levels of measurements -27.964, -32.635, -22.175, -24.567 and -35.083 dBV.

In cases I and J we can see, that there is difference if the fiber is in warm or cold water. This supports fact, that temperature of water can has effect to the sensitivity of optical fiber.

Measuring with soil in Case K (Table 4.15) shows that both arms were sensitive at almost same frequencies and almost same levels of measurements. Specifically, it was sensitive at frequencies 160, 480, 800, 1440 and 1760 Hz for left arm. With measurements -27.964, -32.635, -22.175, -24.567 and -35.083 dBV for each appropriate frequency. For right arm sensitive frequencies are 160, 480, 800, 1120, 1440 and 1760 Hz. With measurements -34.079, -38.511, -32.178, -34.666, -28.057 and -36.430 dBV for each appropriate frequency.

As I mentioned before measurements gathered in Case L (Table 4.16) have something in common with measurements from Case H. Mainly both cases have fiber sensitive at frequencies 10 and 43 Hz, which are also probably caused by resonance. These two cases are the only ones that have these frequencies. Left arm is also sensitive at 480 and 800 Hz. Right arm is sensitive at frequencies 480, 800, 1120 and 1440 Hz. Measurements are lower than measurements in for example Case A. In general we can say, that measurements are approximately three times lower.

Some cells in tables are empty because fiber was not sensitive to specific frequencies.

5 Conclusion

In this bachelor thesis I was dealing with an experiment with Mach-Zehnder interferometer system. Measuring setup was placed on two separate wooden boards isolated by rubber pads from stable construction and from floor. Measuring arm was excited with loudspeaker one meter above wooden boards. Sound waves were generated using frequency generator at 160 Hz with TTL signal and amplitude 10 V. As a source was used LDM-1550-DC-1-FA 1550nm DFB Laser Diode stimulated at 25 °C and current 20 mA, wavelength 1548.59 nm and power 1.74 mW. Measuring setup was 670 cm with attenuation 6.89 dB.

Now let me summarize measured results.

As a conclusion from all above mentioned gathered measurements we can assume that if we want to measure as many frequencies as possible we should use setup from Case H – bending insensitive fiber in mounting foam. Unfortunately this setup provides very low levels of measurements. On the other hand if we want to get as high measurements as possible setup from Case D – fiber closed in two polystyrene boards is the best solution. Other good solution is using setup from Case F – common optical fiber in mounting foam without coupler arms, but as I mentioned before there is disadvantage of high attenuation caused by expansion of mounting foam. For detecting low frequencies we can use two setups either from Case H – bending insensitive fiber in mounting foam or from Case L – fiber glued to wooden board. Second option, Case L – fiber glued to wooden board, is more suitable because we will get higher levels of measurements and there is no problem with high attenuation caused by mounting foam.

In my opinion setups from Case E – only fiber with secondary protection and Case I – fiber in warm water are not very suitable for detecting sensitivity at specific frequencies. Because, as you can see in appropriate tables (Table 4.9 and Table 4.13), fibers were sensitive only at one specific frequency in reference arm.

Furthermore, we can observe, that cases A, B and C achieve same measurements at same frequencies in both arms. Except Case B – bending insensitive fiber that is sensitive also to relatively high frequency 2080 Hz in measuring arm.

In Case C – fiber covered by polystyrene board we can see that fiber in measuring arm is less sensitive at lower frequencies 160 and 480 Hz comparing to Case B and less sensitive in left side comparing to Case A. But at higher frequencies 800 and 1120 Hz is more sensitive than in Case A.

There is big difference between Case I – warm water and Case J – cold water. Measurements in both cases and both arms are almost same. But the difference is that the reference arm is sensitive only at frequency 800 Hz with -11.706 dBV, which is two times higher measurement than at same frequency in reference arm from Case J. And also sensitive frequencies are not same in appropriate arms in each case.

Setup in Case K – fiber in soil has almost same sensitivity like cases A, B or C. But comparing to cases A, B and C Case K is sensitive at higher frequencies in both arms. With regard to sensitivity Case K is sensitive at same frequencies as Case D, but measurements in Case K achieves significantly lower sensitivity.

6 Bibliography

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Annex

Bachelor thesis includes DVD.

Directory structure of attached DVD:

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/L

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/R

Annex.A: All measurements results in one table

Frequency [Hz]		10	43	160	320	480	800	1120	1440	1760	2080	2720	3040
Case A	L – Value [dBV]	-	-	-22.116	-	-21.251	-27.869	-26.018	-29.477	-	-	-	-
	R – Value [dBV]	-	-	-29.592	-	-30.221	-21.109	-20.777	-	-	-	-	-
Case B	L – Value [dBV]	-	-	-23.808	-	-23.125	-18.583	-26.311	-	-	-31.448	-	-
	R – Value [dBV]	-	-	-17.201	-16.238	-	-22.431	-23.735	-	-	-	-	-
Case C	L – Value [dBV]	-	-	-30.250	-	-27.460	-21.645	-23.442	-	-	-	-	-
	R – Value [dBV]	-	-	-21.011	-31.210	-30.140	-19.792	-22.618	-	-	-	-	-
Case D	L – Value [dBV]	-	-	-13.096	-	-8.078	-8.078	-6.994	-14.504	-13.670	-	-	-
	R – Value [dBV]	-	-	-18.514	-	-11.530	-6.399	-	-12.181	-	-11.707	-	-
Case E	L – Value [dBV]	-	-	-18.576	-	-21.078	-21.244	-	-34.308	-	-	-	-
	R – Value [dBV]	-	-	-15.662	-	-	-	-	-	-	-	-	-
Case F	L – Value [dBV]	-	-	-13.462	-	-13.194	-5.082	-16.538	-	-17.506	-	-	-
	R – Value [dBV]	-	-	-11.787	-	-15.264	-2.984	-9.680	-	-	-	-	-
Case G	L – Value [dBV]	-	-	-47.269	-	-56.370	-	-	-	-	-	-	-
	R – Value [dBV]	-	-	-59.691	-	-	-49.116	-53.141	-61.647	-	-	-	-
Case H	L – Value [dBV]	-74.485	-73.872	-72.571	-	-75.452	-73.416	-75.940	-74.135	-	-79.461	-78.498	-80.907
	R – Value [dBV]	-	-65.760	-65.880	-	-	-68.940	-66.728	-68.046	-77.176	-76.978	-	-
Case I	L – Value [dBV]	-	-	-31.524	-	-	-24.867	-26.770	-32.594	-	-	-	-
	R – Value [dBV]	-	-	-	-	-	-11.706	-	-	-	-	-	-
Case J	L – Value [dBV]	-	-	-	-	-29.801	-18.182	-29.597	-	-	-	-	-
	R – Value [dBV]	-	-	-27.964	-	-32.635	-22.175	-	-24.567	-35.083	-	-	-
Case K	L – Value [dBV]	-	-	-27.964	-	-32.635	-22.175	-	-24.567	-35.083	-	-	-
	R – Value [dBV]	-	-	-34.079	-	-38.511	-32.178	-34.666	-28.057	-36.430	-	-	-
Case L	L – Value [dBV]	-56.636	-53.939	-	-	-56.591	-62.059	-	-	-	-	-	-
	R – Value [dBV]	-61.340	-57.167	-	-	-54.998	-53.841	-62.108	-63.479	-	-	-	-